POWER MODULE COOLING FOR FUTURE ELECTRIC VEHICLE APPLICATIONS: A COOLANT COMPARISON OF OIL AND PGW

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ABSTRACT

Compact and efficient power converters are being developed to support the needs of future ground vehicle systems. This progress is being driven by component advancements, combined with improvements in component thermal management achieved through various liquid cooling implementations. Regardless of the configuration of the thermal management system, the properties of the liquid coolant used are vital to its performance. This work compares the use of turbine oil and an aqueous glycol solution as coolants in an automotive based power converter application.

1. INTRODUCTION

Advancements in power electronic conversion system technologies will enable next generation ground vehicles to fulfill increasingly demanding mission objectives. DC-DC converter and inverter systems slated for future propulsion, survivability, and lethality applications, operate at power levels on the order of 100 kW and above. Even with very high efficiencies, the components of these systems produce kilowatts of power loss in the form of heat. Benefits can be realized by improving thermal management of active and passive system components. However, more effective cooling of active electronic devices can also enable higher output power at the converter's system level.

The most widely used implementation for thermal management of active electronic components is an air cooled heat sink approach. In its simplest and most primitive form, air cooling is achieved passively through natural convection. Improved heat dissipation can be realized by the addition of forced air flow channeled in both laminar and impinging directions. However, as system volumetric power densities increase, inherent material properties preclude an air cooled approach. Other cooling methods, such as thermoelectric and active spray cooling have been demonstrated with promising results. However, widespread implementation of these techniques has not yet occurred.

Presently, liquid cooling is the most viable approach to meet system design parameters and has been used in a variety of industrial and military applications. In vehicle systems, automotive fluids such as engine oil and engine coolant are readily available for electronic cooling applications. Future military vehicle system design requirements have varied between using one of these two fluids. However, neither fluid is optimized for power component heat exchange in composition or operating temperature. Factors such as electrical conductivity, density, viscosity, specific heat, and thermal conductivity, can make one fluid more suitable than the other. This paper presents performance and material property data for Castrol 399 turbine oil and 50% by weight aqueous solutions of ethylene (WEG) and propylene (PGW) glycol. PGW is replacing WEG in most automotive applications because it offers nearly identical properties without the toxic environmental effects. Results of experiments conducted using both Castrol 399 and PGW as cooling fluids are shown. From these results, conclusions are drawn regarding their use in cooling system designs.

2. FLUID PROPERTIES

Using fluid as a coolant in an electrical system appears counterintuitive because many fluids are electrically conductive. Of the two types of automotive fluids considered, aqueous glycol solutions are electrically conductive, while engine oils are not. As a result, oil has the advantage of being used in direct contact with electrically active heat generating surfaces. By contrast, aqueous glycol solutions require the active surface to have an electrical isolation layer, thereby increasing the thermal resistance of the interface.

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Performance of liquid cooled heat exchangers is impacted by the fluid flow rate, which is directly related to fluid density and viscosity. Castrol 399 and WEG have comparable fluid densities which do not vary significantly with temperature [1,2]. However, the viscosity of both coolants does greatly vary over the temperature range. Castrol 399 has a viscosity that is approximately five times higher than that of WEG for a given cooling system operating temperature between 25º C and 80º C. The change in oil viscosity over this range is also nearly twice as large as that of WEG, which negatively impacts the overall system pump requirements at low temperatures [1,2].

Two important properties affecting the thermal transfer capability for fluids are specific heat and thermal conductivity. Specific heat is the measure of the temperature rise of a given volume of material as a function of its absorption of thermal energy. At 50º C, Castrol 399 has a specific heat of 2.0 ($kJ \cdot kg^{-1} \cdot K^{-1}$), compared to 3.5 ($kJ \cdot kg^{-1} \cdot K^{-1}$) for WEG [1,2]. Therefore, a given volume of Castrol 399 will exhibit nearly twice the temperature rise as that of WEG for the same amount of absorbed thermal energy. Thermal conductivity is a metric of the ability of a material to internally transfer thermal energy. Between 25º C and 80º C, the thermal conductivities of Castrol 399 and WEG are approximately 0.15 ($W \cdot m^{-1} \cdot K^{-1}$) and 0.40 ($W \cdot m^{-1} \cdot K^{-1}$), respectively [1,2]. For a given volume, geometry, and thermal power input for each fluid, the maximum temperature of Castrol 399 can be nearly three times that of WEG. Table 1 displays the values of the properties discussed for Castrol 399 and WEG.

Table 1. Fluid Property Values (40º C)

Fluid	Castrol 399	WEG
Density ($kg \cdot m^{-3}$)	937	1058
Viscosity ($mPa \cdot s$)	15.3	2.3
Specific Heat ($kJ \cdot kg^{-1} \cdot K^{-1}$)	2.0*	3.5*
Thermal Conductivity ($W \cdot m^{-1} \cdot K^{-1}$)	0.15	0.40*

* Data values reported at 50º C.

3. EVALUATION PLATFORM

A major part of the Army Research Laboratory's (ARL) hybrid electric vehicle research and development program, funded through TARDEC, is the design and fabrication of a high power bi-directional DC-DC converter (BDC). This converter manages power flow between the lower voltage battery pack and the higher voltage propulsion power bus. Under conventional operating conditions, propulsion power is provided by a generator, driven by a diesel engine. However, during periods of high power demand, such as vehicle acceleration, high torque conditions, or loading from auxiliary subsystems, the BDC operates in boost-mode by stepping-up the battery voltage and providing additional power to the propulsion bus. Conversely, under light propulsion loads, the BDC operates in buck-mode, stepping-down the high voltage from the propulsion bus and recharging the battery bank [3]. Fig. 1 shows the ARL 90 kW BDC test bed platform. The circuit design of the 90 kW BDC test platform consists of three-phases each using a common half-bridge IGBT switch module with incorporated anti-parallel diodes. This type of module is readily available due to its widespread use in both DC and AC power conversion systems.

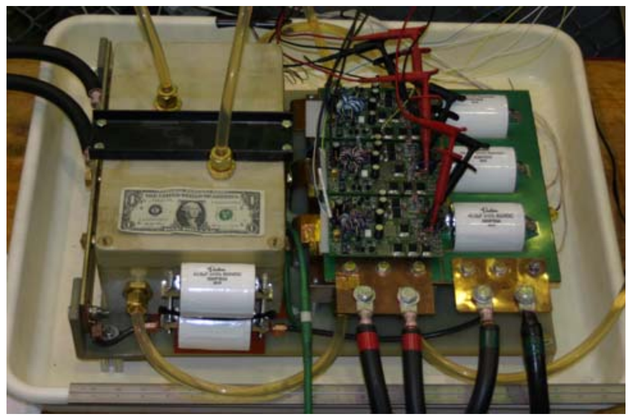

Fig. 1. ARL 90 kW bi-directional converter platform.

For this study, the test platform was modified to operate as a single-phase boost converter. Fig. 2 shows the corresponding circuit diagram with Q_1 and Q_2 representing the half-bridge IGBT switch module [3]. The diagram shows the low voltage battery (LS) and high voltage propulsion bus (HS). This implementation facilitated acquiring thermal imaging data of the IGBT die surfaces. Additionally, this configuration ensures a known power flow through the individual module tested without compromising converter function.

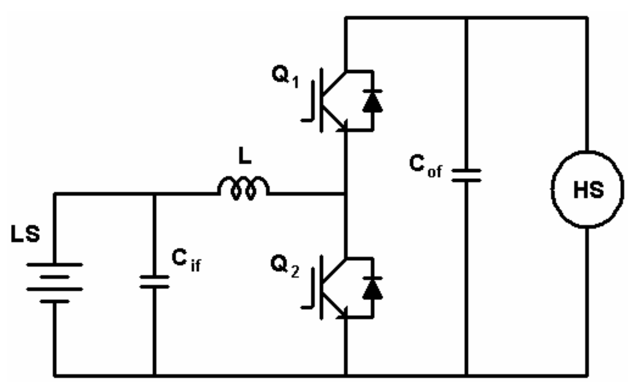

Fig. 2. Single-phase boost converter diagram.

To evaluate the performance of Castrol 399 and PGW, the IGBT switch module was mounted on a D6 Industries liquid cold plate (Hydroblok-A1-4P-06). Castrol 399 was pumped through the cold plate using a Mydax heat exchanger to regulate flow rate and inlet oil temperature. After internally cleaning the oil from the cold plate, PGW testing was conducted using a Julabo heat exchanger. Arctic Silver® thermal compound was applied to the cold plate and component interface. The module used in the evaluation was a commercially available Powerex CM400DU-24NFH dual 400 A, 1200 V IGBT half-bridge module. This part contains IGBT die optimized for fast switching applications. Compared to other modules, the switching losses are lower while the conduction losses are higher. The module case was opened and the protective potting compound was removed to expose the die surfaces for thermal imaging, as shown in Fig. 3. For accurate infrared (IR) thermal measurement, the die surfaces were uniformly coated with boron nitride [4]. IR imaging of the active IGBT die surfaces was achieved using a FLIR ThermaCAM SC500.

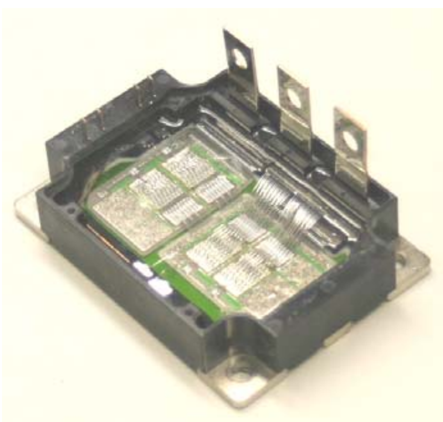

Fig. 3. Exposed IGBT half-bridge module.

During testing, the converter was operated using open loop control at various output power levels ranging from 5 kW to 30 kW with each cooling fluid. The input voltage level was 300 V with an output load voltage of 600 V and the switching frequency was 17 kHz. Based on the inductor value, the converter operated in discontinuous conduction mode during all tests. This mode of operation minimizes the turn-on switching loss of the IGBT and decreases the diode loss.

4. EXPERIMENTAL RESULTS

The experimental test setup was configured for the Castrol 399 coolant at a heat exchanger set point of 25º C. A resistive load bank was used to step the converter output power through the operating range. Each power level test point was maintained for five minutes to attain thermal equilibrium of the IGBT die. This test procedure was repeated with the temperature set point of the Castrol 399 raised to 50º C. The cooling loop was then configured for PGW and tests were conducted at both 25º C and 50º C. Table 2 summarizes the flow rates of the fluids during the tests. For each power level test point, the active die surface temperature was measured with the IR camera and a thermal image was captured. Fig. 4 shows thermal images of the device for each cooling fluid at 25º C and 25 kW output. The left image shows the thermal effects of PGW cooling while the right image shows the effects of Castrol 399 cooling. The spectrum of these images reveals that the oil cooled device had a significantly higher operating temperature (114º C) than the PGW cooled device (78º C).

Table 2. Coolant Flow Rates for Tests

Fluid	Castrol 399		PGW	
Temperature (º C)	25	50	25	50
Flow Rate (gpm)	1.51	1.61	1.55	1.37

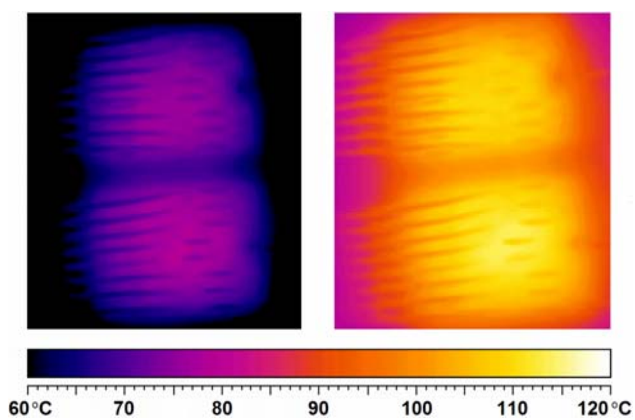

Fig. 4. Die thermal images at 25 kW output, 25º C Coolant (PGW left, Castrol 399 right).

Fig. 5 shows a graph of test data relating maximum die temperature to the converter output power level for both Castrol 399 and PGW at 25º C. Similarly, Fig. 6 presents 50º C coolant test data. To provide sufficient safety margin for protecting the IR camera from device failure, maximum operating temperature of the IGBT die was limited to 120º C. The 27 kW test data of Fig. 5 shows that the IGBT temperature reached 120º C when cooled with Castrol 399, compared to only 84º C when cooled with PGW. Likewise, the 20 kW test data of Fig. 6 shows that the IGBT temperature reached 116º C when cooled with Castrol 399, compared to only 92º C when using PGW. The trend of the data reveals that when using Castrol 399, over a 3º C rise in die surface temperature occurs for each kilowatt increase in converter output power. Similarly, PGW exhibits a 2º C rise in die surface temperature for each kilowatt increase in converter output power.

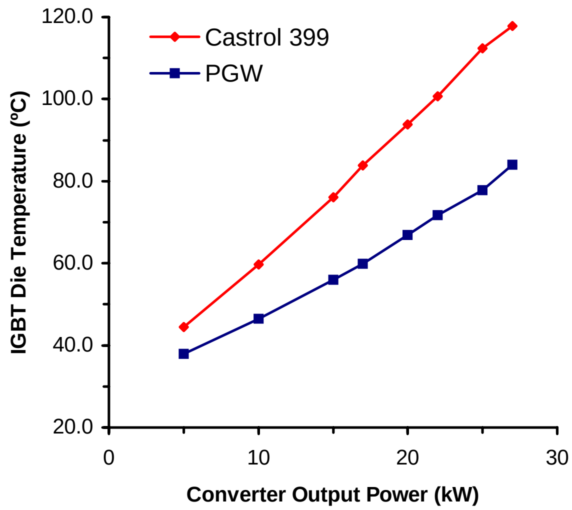

Fig. 5. Fluid comparison at 25º C coolant temperature.

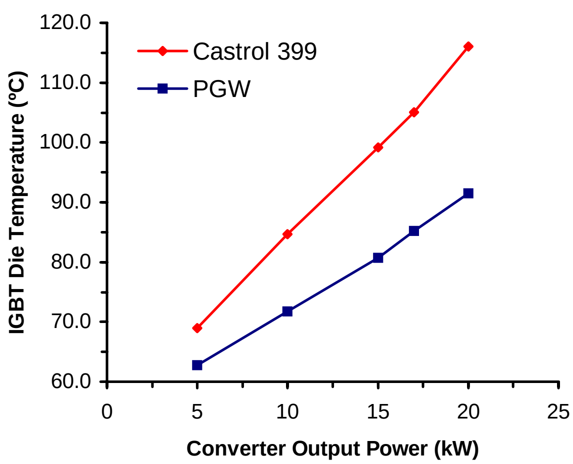

Fig. 6. Fluid comparison at 50º C coolant temperature.

5. CONCLUSION

The combination of several factors makes one cooling fluid more favorable than another for use as a liquid coolant in electrical systems. Onboard a vehicle having stringent space and weight limitations, using an already available vehicle fluid for cooling electronic systems is recommended. Both engine oil and aqueous glycol solutions have been proposed as coolants for vehicle power converters. However, several physical factors make aqueous glycol solutions the better performing and more favorable choice of coolant over engine oil. Despite the desirable electrical insulating property of oil, many of its other properties contribute to its poor performance as a cooling fluid.

The expression of temperature rise as a function of power is commonly known as thermal resistance. Achieving high volumetric power density in electronic systems requires an optimization of thermal performance, which means that the system thermal resistance must be minimized. Using Castrol 399 oil as coolant yielded a 50% increase in overall thermal resistance compared to the same system using PGW as coolant. This significant result can be viewed from two vantage points. First, for a given maximum operating temperature of a power converter, using an aqueous glycol solution instead of engine oil as coolant enabled system power to be increased by 50%. Second, for a power converter operating at a specific load point, the temperature rise of the system when cooled with an aqueous glycol solution can be half as much as the temperature rise of the same system when cooled with an engine oil.

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